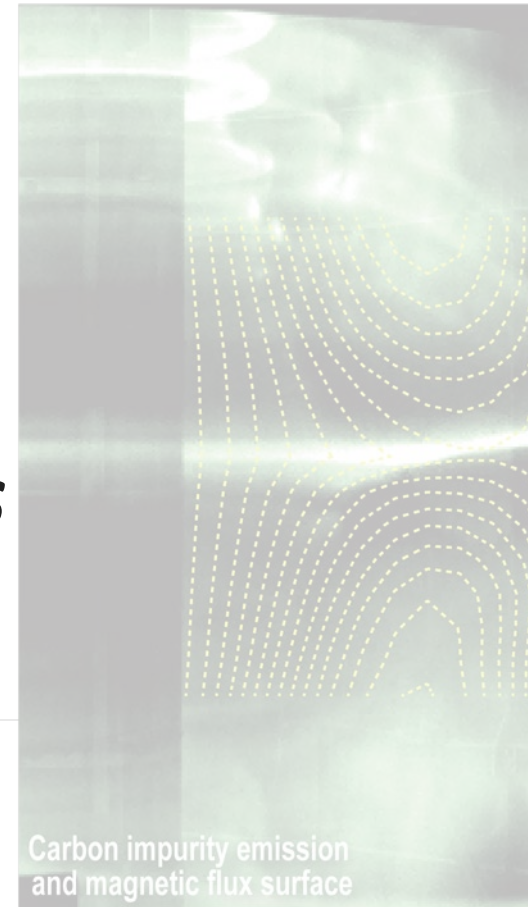




The 21st International Spherical Torus Workshop

Overview of UTST/TS-6 ST merging startup experiments

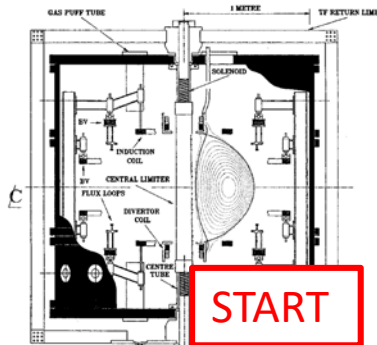
*M. Inomoto, H. Tanabe, Y. Ono,
and TS group (Univ. Tokyo)*



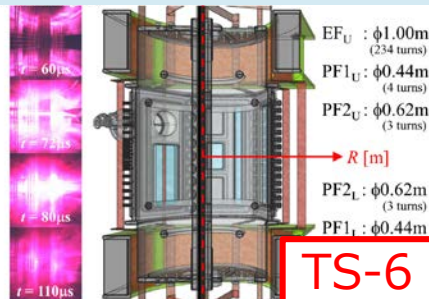
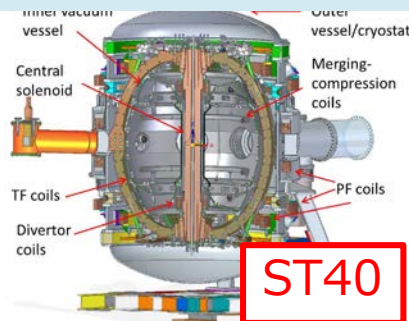
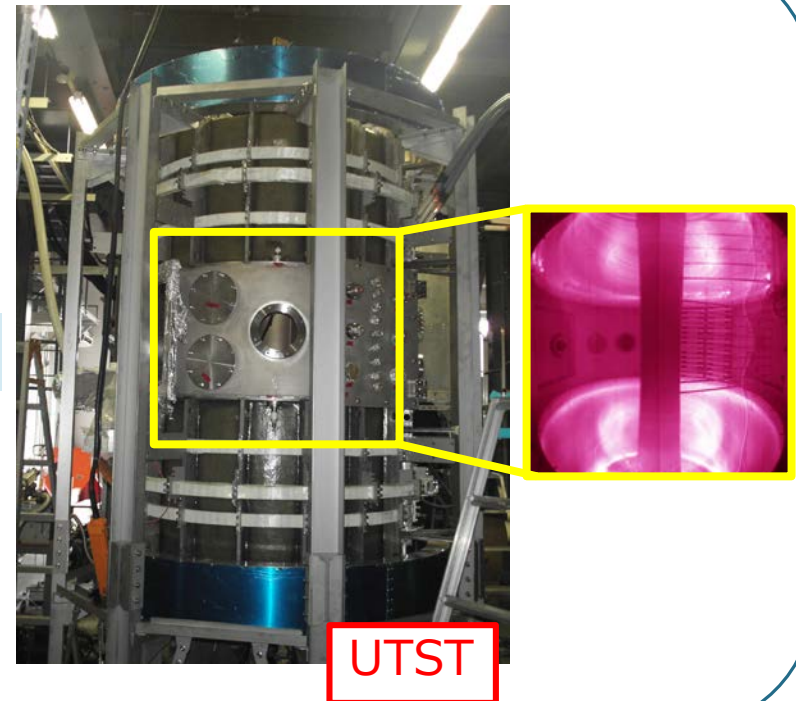
Carbon impurity emission
and magnetic flux surface

Background of this research

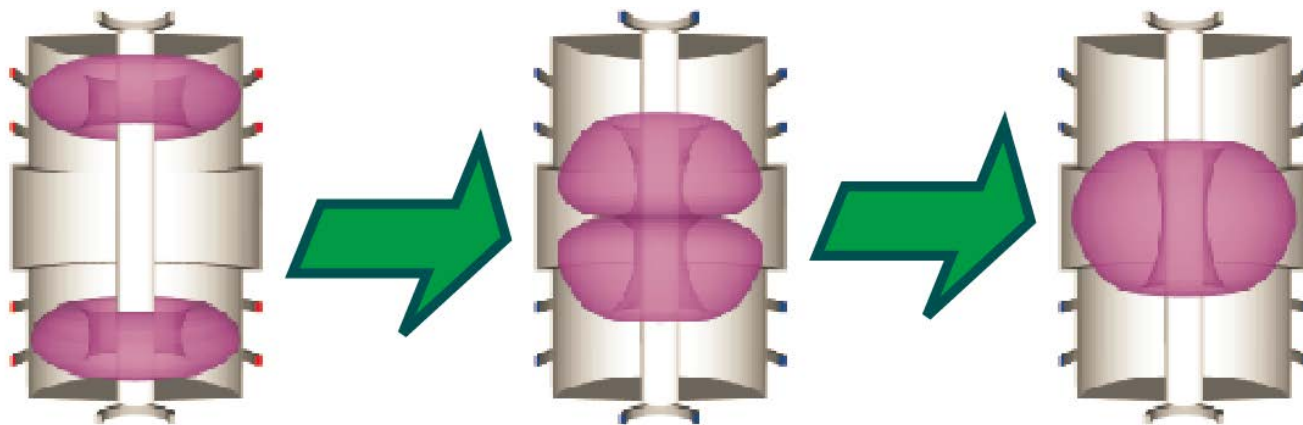
Torus plasma merging technique is employed to obtain high performance fusion plasmas **by reconnection heating** and is applied to **spherical tokamak (ST)** devices.



Spherical Tokamak devices using merging method



Axial merging of ST plasmas

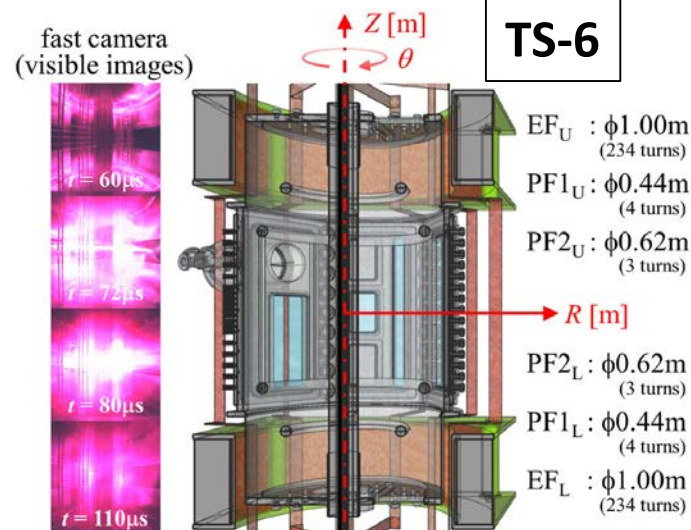


1. Two initial ST plasmas are formed inductively by poloidal field.

2. Two ST plasmas move towards device center and merge through **magnetic reconnection**.

Differently from typical magnetic reconnection of anti-parallel fields, ST merging formation involves strong toroidal field (called 'guide' field) perpendicular to the reconnecting poloidal fields.

TS-6 and UTST devices



TS-6 Typical parameters

$$n_e < 1 \times 10^{20} [\text{m}^{-3}]$$

$$T_e, T_i \sim 10 [\text{eV}] \quad (\text{initial plasma})$$

$$T_e < 30 [\text{eV}], T_i < 60 [\text{eV}] \quad (\text{after merging})$$

$$\text{Guide field } B_{t0} \sim 0.15 [\text{T}]$$

$$\text{Reconnection field } B_p \sim 0.03 [\text{T}]$$

$$R \sim 17 \text{ cm} / a \sim 10 \text{ cm} (A \sim 1.7)$$

UTST Typical parameters

$$n_e < 5 \times 10^{19} [\text{m}^{-3}]$$

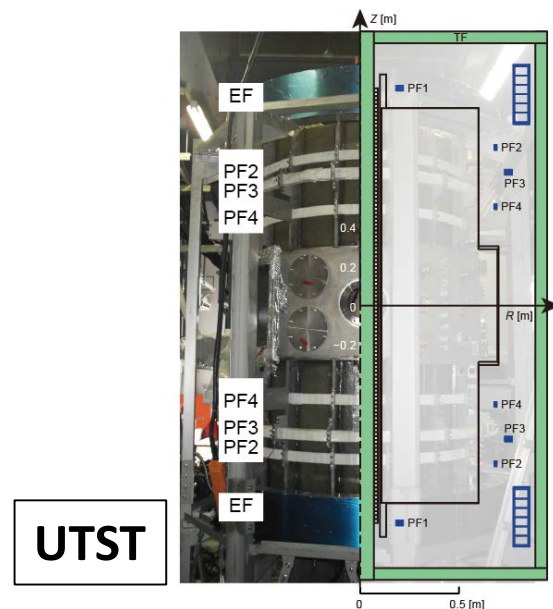
$$T_e, T_i \sim 10 [\text{eV}] \quad (\text{initial plasma})$$

$$T_e < 30 [\text{eV}] + \text{tail}, T_i < 40 [\text{eV}] \quad (\text{after merging})$$

$$\text{Guide field } B_{t0} \sim 0.25 [\text{T}]$$

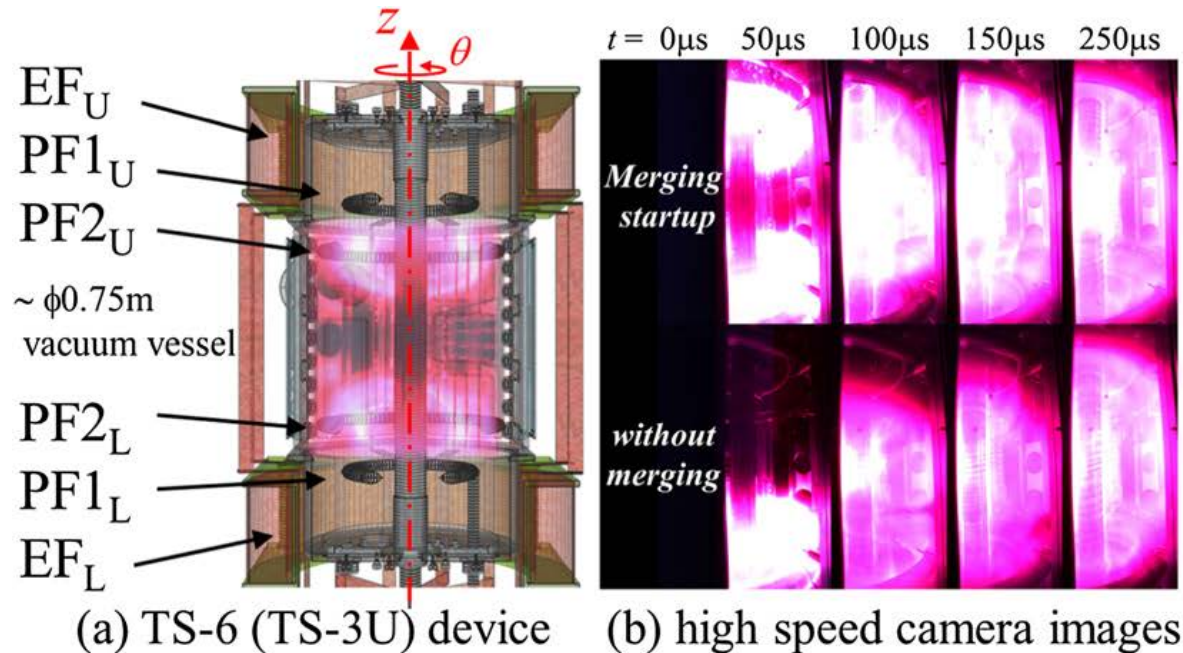
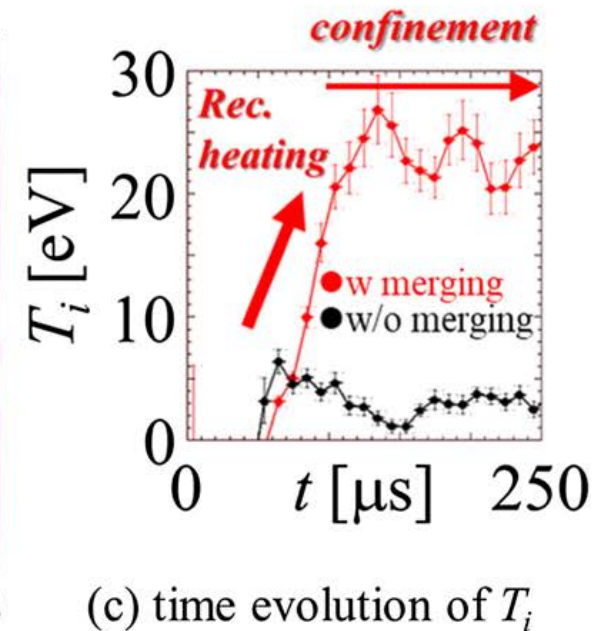
$$\text{Reconnection field } B_p \sim 0.01 - 0.02 [\text{T}]$$

$$R \sim 35 \text{ cm} / a \sim 24 \text{ cm} (A \sim 1.6)$$



Merging start-up in TS-6

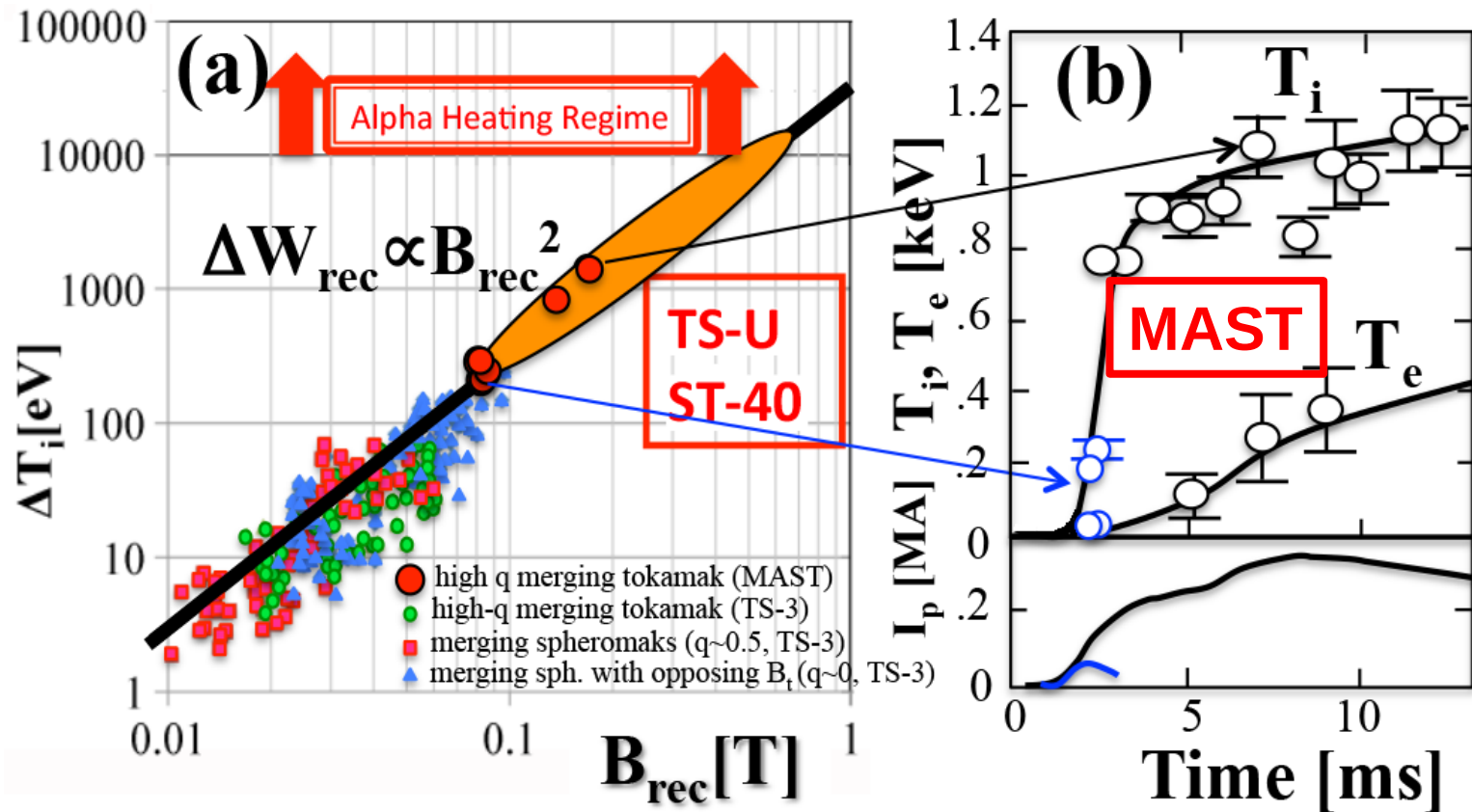
H. Tanabe *et al* 2021 *Nucl. Fusion* **61** 106027



PF2U/L coils located inside the vessel are used to produce initial STs

Reconnection ion heating power
 $> 10 \text{ MW/m}^3$.

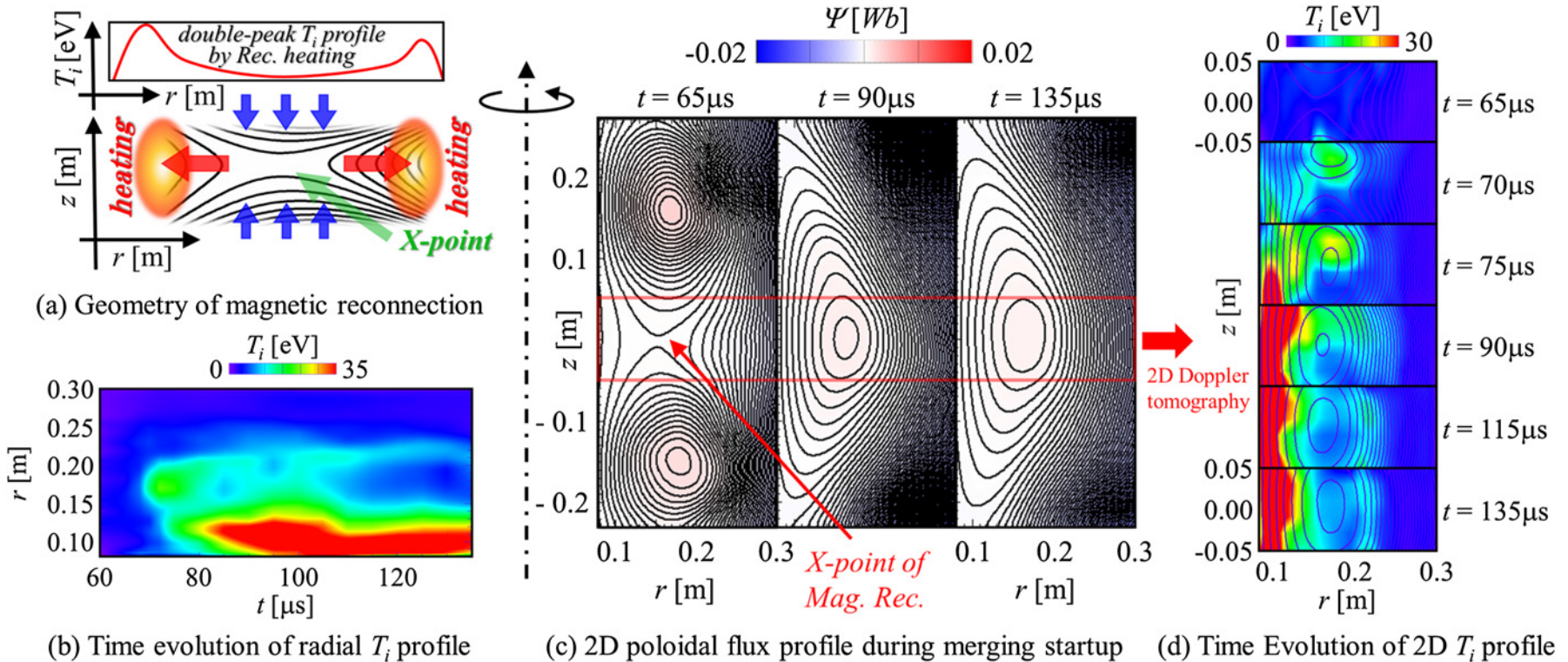
Ion heating scales as $\Delta T_i \propto B_{rec}^2$



As predicted in a 2D steady state model, reconnection process converts the released magnetic energy mostly to ion energy.

Hollow T_i in merged ST (TS-6)

H. Tanabe *et al* 2021 *Nucl. Fusion* **61** 106027



Ions are mostly heated in the downstream regions of reconnection. The hot spots extend along the field lines to form hollow (ring-like) T_i profile of merged ST.

Energy conversion during GF Reconnection

It is generally recognized that large part of the released magnetic energy is converted to (A) ion energy in the downstream (outflow) region.

(B) Electron acc. ($v_{\parallel}$) at X-point

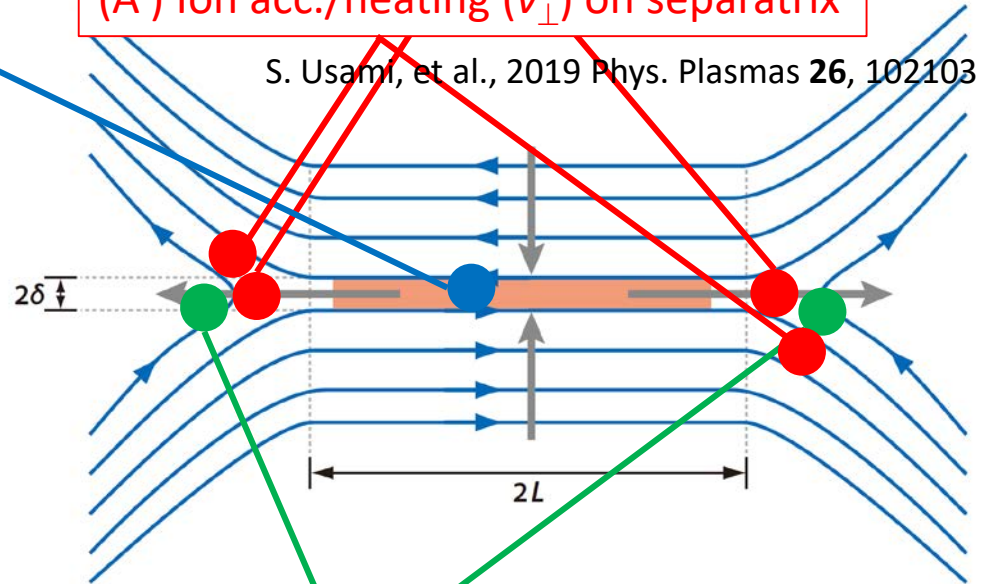
At the X-point, magnetic field and inductive electric field are both in toroidal direction, leading to (B) electron parallel acceleration.

Magnetic field and inductive electric field are close to parallel. Does it cause parallel electron acceleration?

(A) Ion outflow acceleration ($v_{\perp}$)

(A') Ion acc./heating ($v_{\perp}$) on separatrix

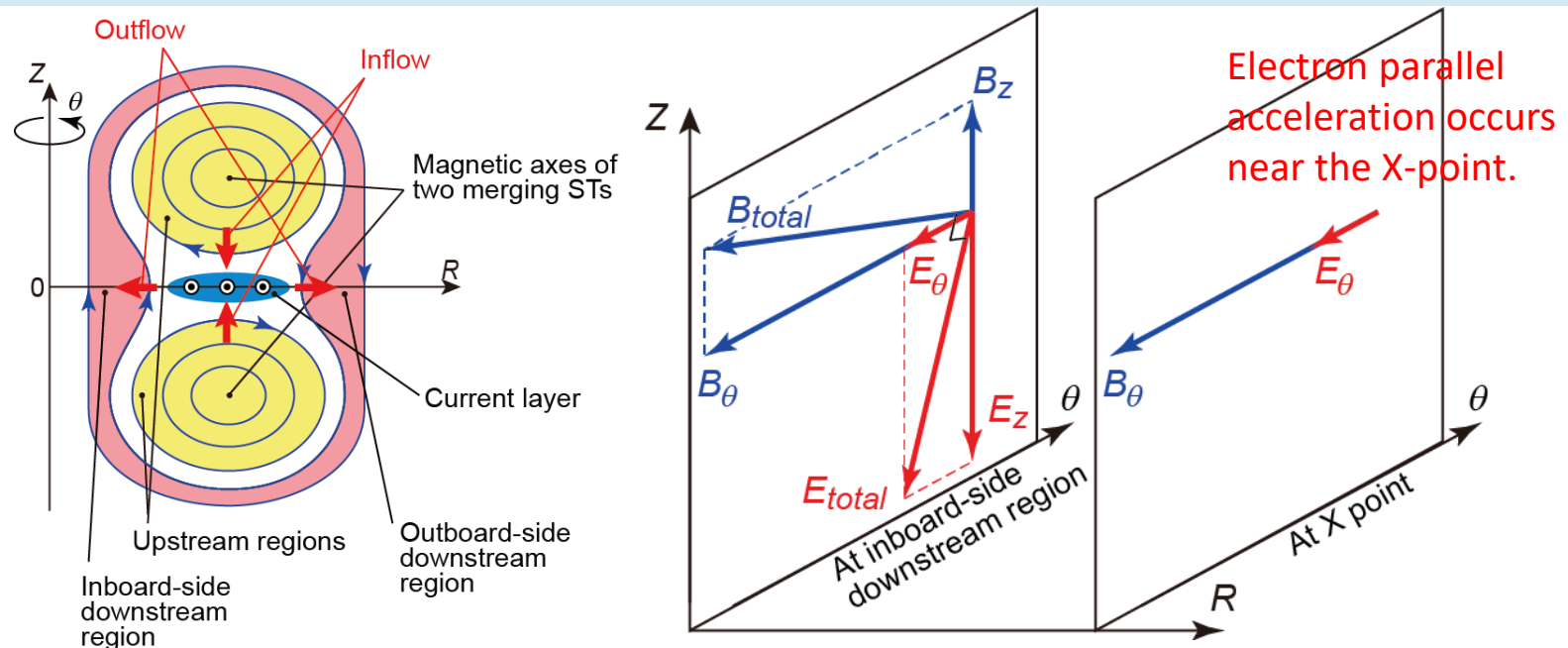
S. Usami, et al., 2019 Phys. Plasmas **26**, 102103



(B') Electron acc. ($v_{\parallel}$) at downstream?

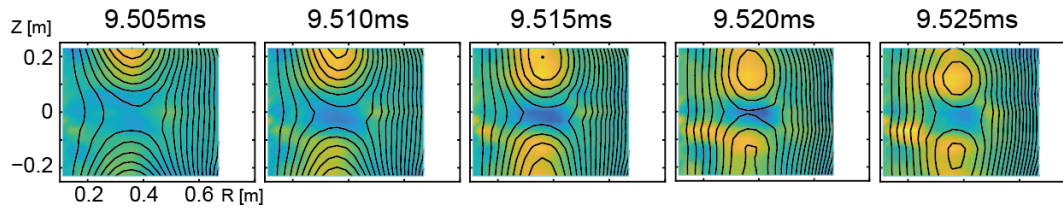
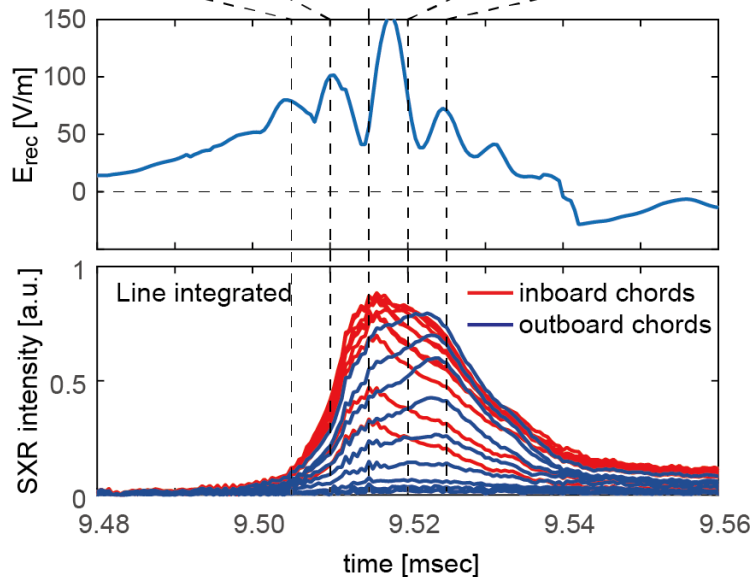
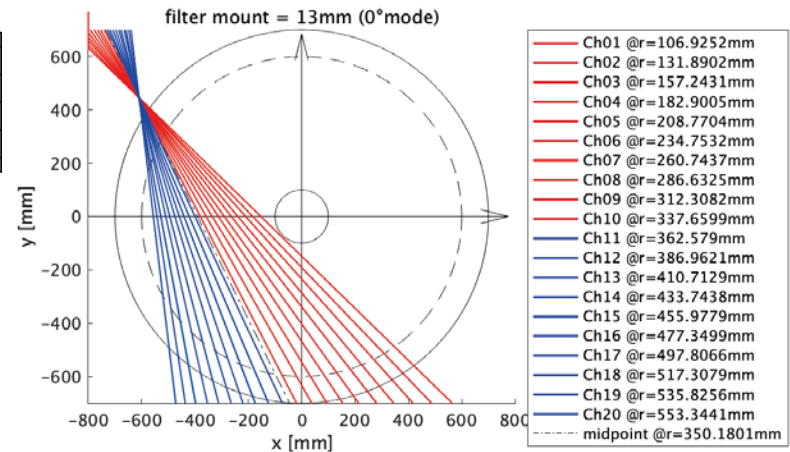
E field in downstream region

Since electrons and ions move inversely by the parallel electric field along the slightly tilted magnetic field line in the outflow region, axial charge separation develops to suppress the parallel electric field.



In the downstream region of guide field reconnection, **ion outflow** and **electron parallel acceleration** are in trade-off relationship.

SXR emission during merging (UTST)

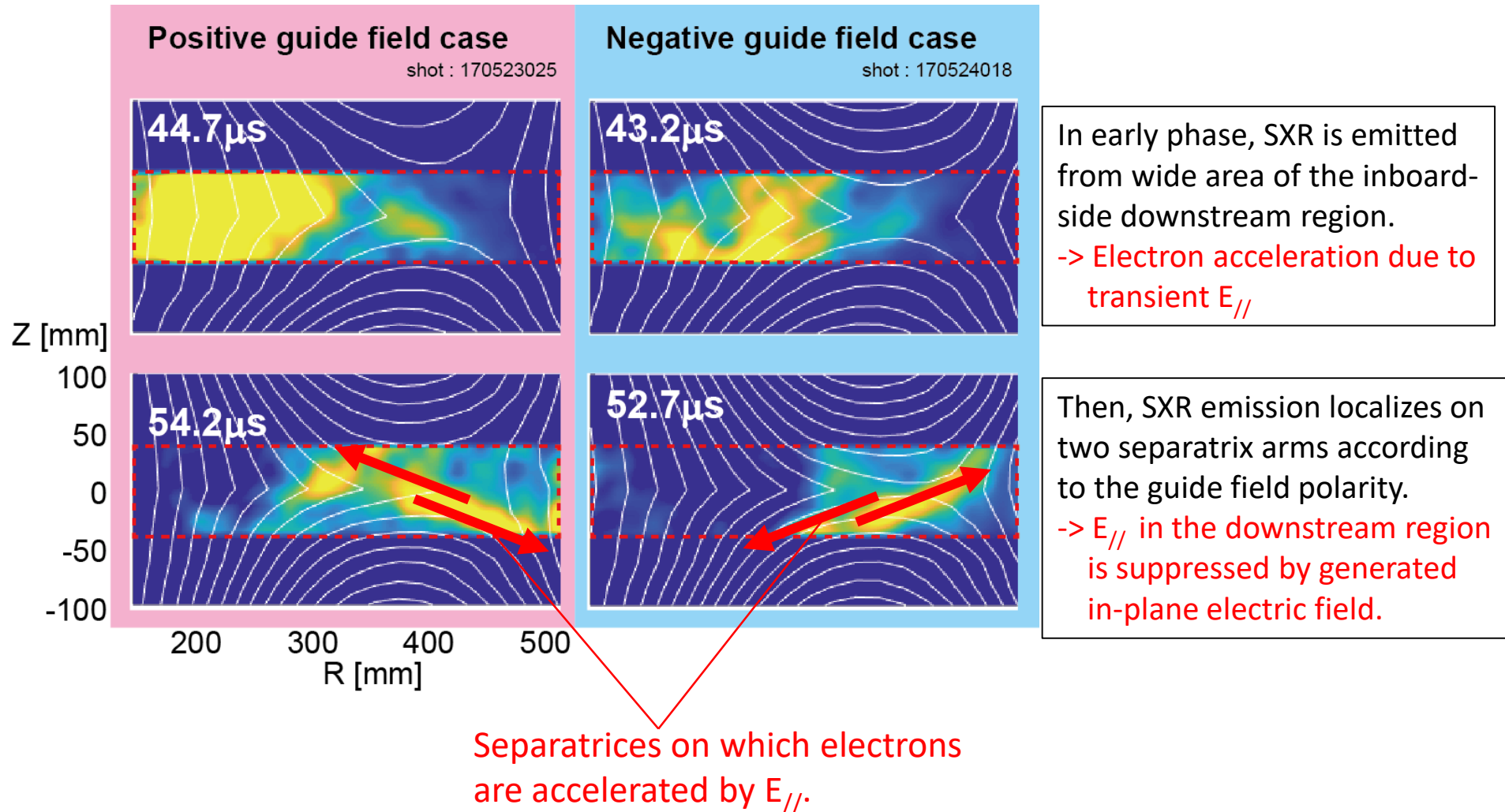


**SXR emission concentrates
[initially] inboard (downstream) region
-> [later] outboard (X-point) region.**

SXR signal, which represents the location of accelerated electrons, quickly increases within $5 \mu\text{s}$, and then its profile changes with $\sim 10 \mu\text{s}$ timescale while the radius of the reconnection X-point stays $R \sim 0.36 - 0.39 \text{ m}$.

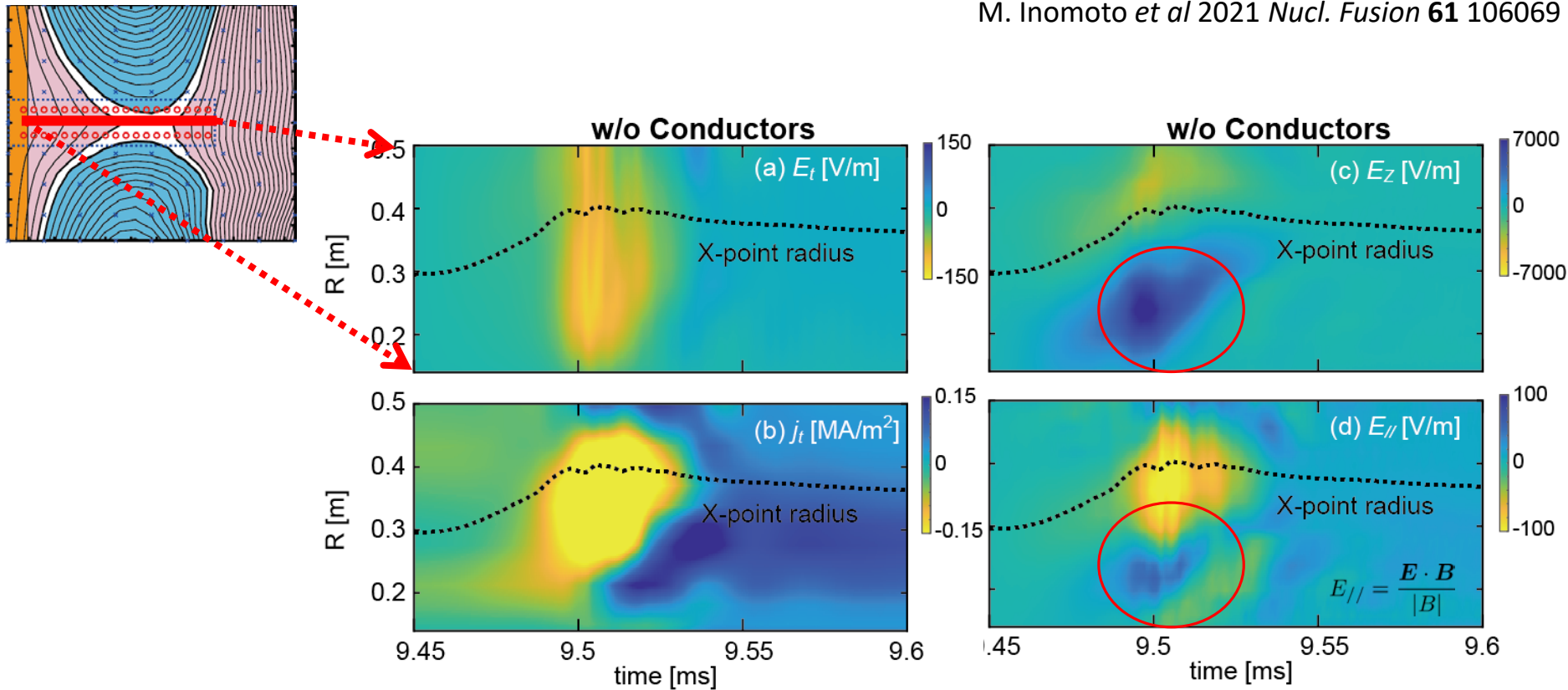
SXR emission (standard case w/o limiter)

M. Inomoto *et al* 2019 *Nucl. Fusion* **59** 086040



Electric field structure

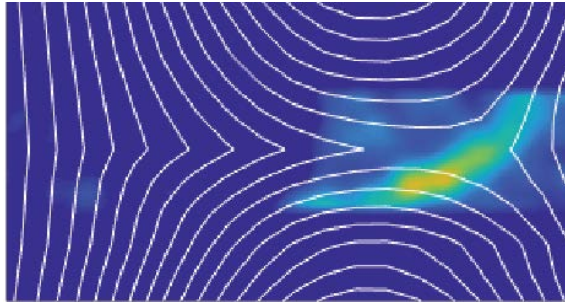
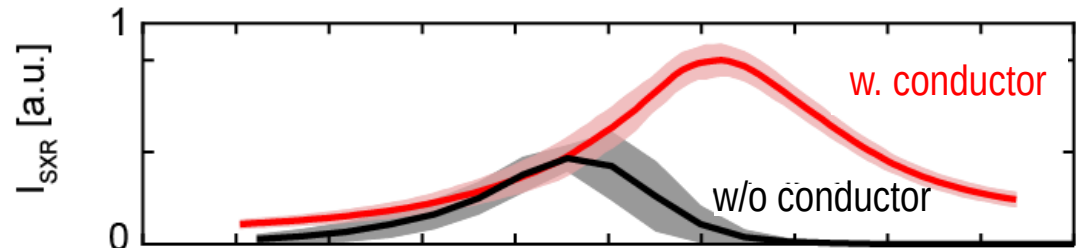
M. Inomoto *et al* 2021 *Nucl. Fusion* **61** 106069



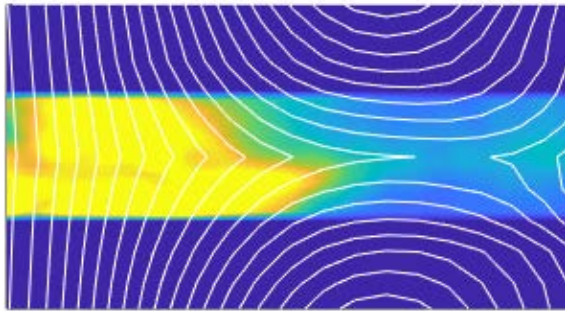
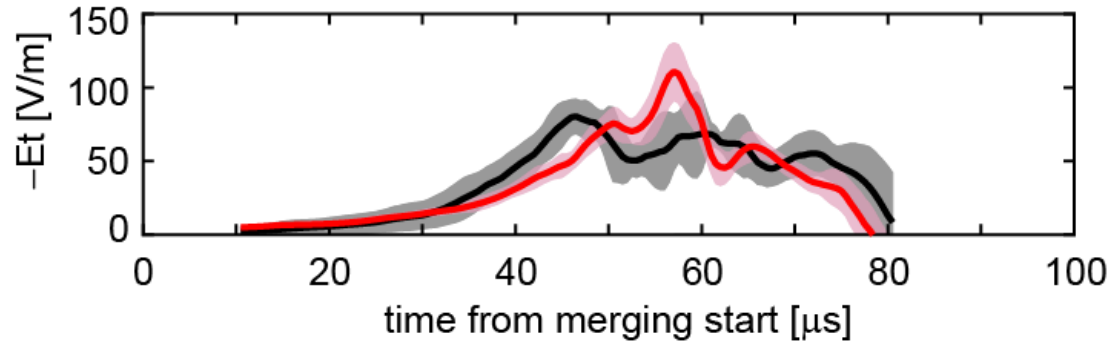
- Because of the high guide-field, large in-plane electric field E_z was generated to suppress $E_{//}$ in the downstream region.

Electron acceleration kept longer with inboard limiter conductor plates

w/o inboard limiter conductor

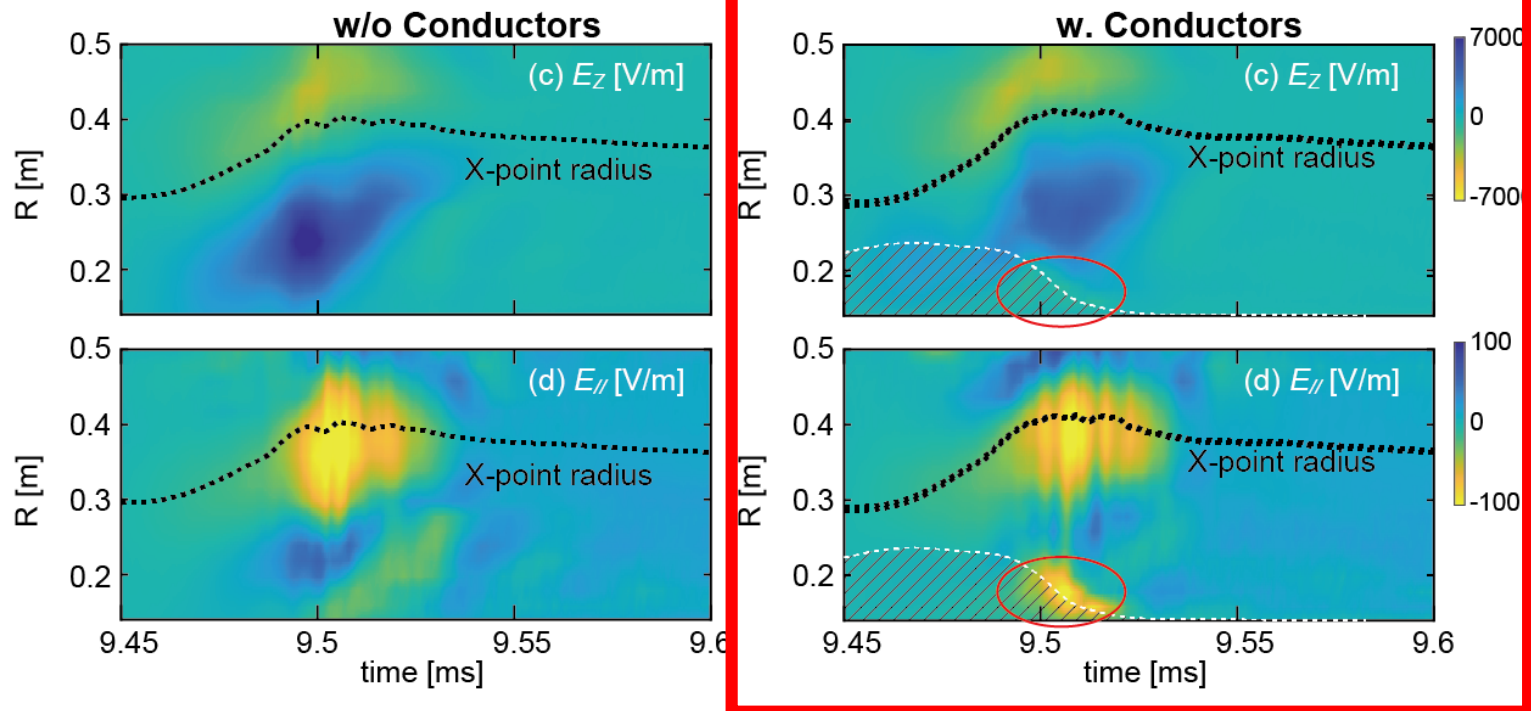


with inboard limiter conductor



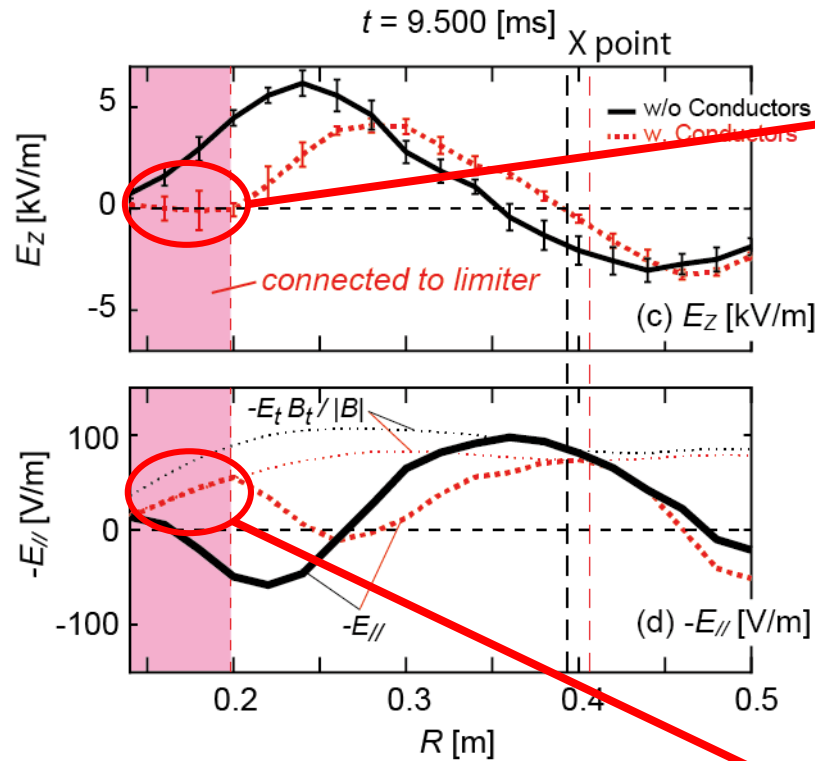
Installation of inboard conductors largely changed the SXR emission spatial profile and evolution while reconnection parameters (current, electric field, etc.) inside the diffusion region did not show significant change.

E_z and $E_{//}$ with/without limiter conductor



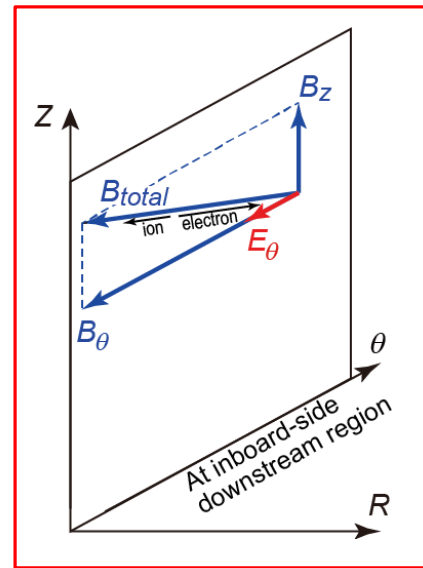
- In-plane electric field E_z was largely cancelled by the short-circuit effect of conductors, resulting in large $E_{//}$ remaining.

E_z mostly suppressed by conductors

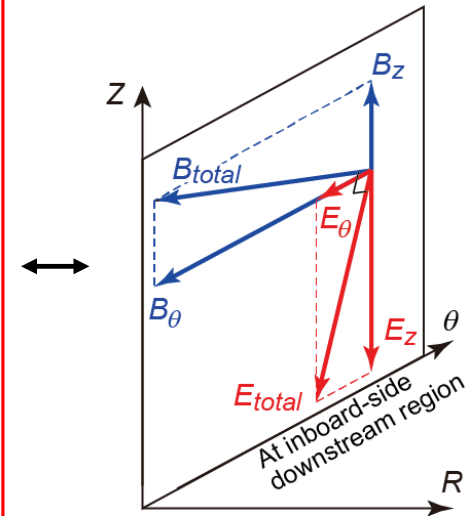


E_z suppression by conductors

w. conductors



w/o conductors

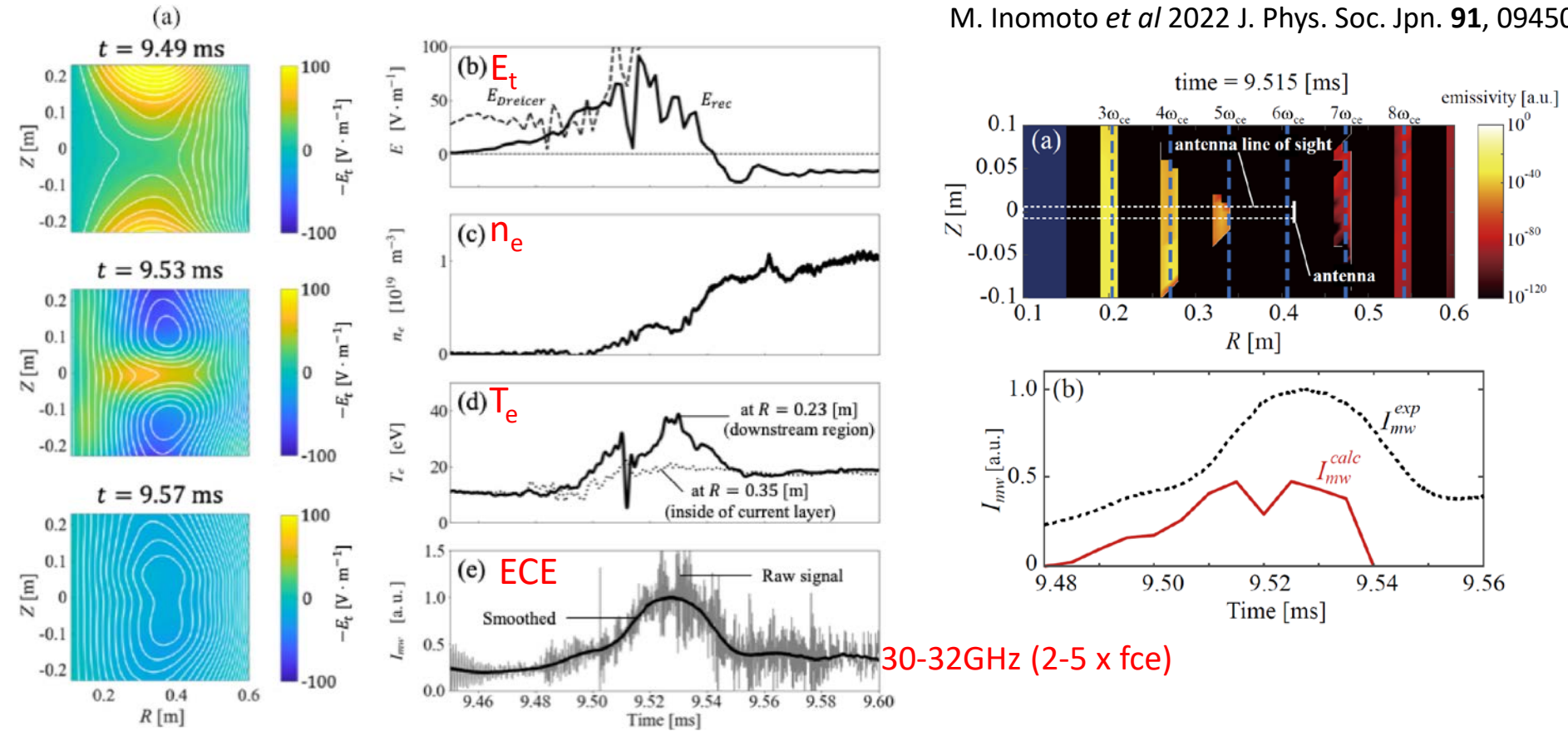


$E_{//}$ survives in the downstream region

particle acceleration

ECE during merging (UTST)

M. Inomoto *et al* 2022 J. Phys. Soc. Jpn. **91**, 094501



ECE signal also increases only during the merging phase. Numerical calculation results suggest that emission from inboard side downstream region dominantly contributes to the total emission through momentum conversion by classical collision.

Summary

Merging start-up of ST plasmas will provide high-power heating of ions through magnetic reconnection.

In-plane E plays important role to determine the energy conversion mechanism.

- ✓ In-plane E in the downstream is necessary for ion outflow (translational motion) and that on the separatrix for ion heating (gyration).
- ✓ In-plane E in the downstream region is affected by the boundary condition of vacuum vessel.